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VARIATIONS IN THE BAINITE HARDENABILITY OF ASTM A723 STEEL

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Austenite transformation characteristics were determ_ned for ASTM A723 steels prepared by various suppliers and refining methods. Standard measurement techniques as well as differential thermal analysis and thermomagnetic analysis were employed.

Remarkably large variations in hardenability are found among these steels; the variations appear to be due to differences of less than one percent in the

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20. ABSTRACT (CONT'D)

nickel content among the samples. These hardenability properties are shown to correlate in a straightforward way with mechanical properties of large size components that were quenched at different rates.

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INTRODUCTION

The austenite transformations of ASTM A723 are often assumed to be described by the TTT diagram obtained by Heheman and Troiano (ref 1) for a very similar alloy. The primary difference is the presence of vanadium (0.1%) and copper (0.1%) in A723. A key transformation characteristic for this alloy is the bainite hardenability. It is important to know the extent to which the transformation characteristics have changed due to the composition differences in order to properly tailor the heat treatment of large components. Unfortunately, the standard laboratory test for hardenability, which is the Jominy end quench test, is not suitable for A723 because of the relatively high hardenability of this steel.

A method that we have developed for studying transformations in ferrous alloys has proven to be very helpful for questions pertaining to hardenability in these high hardenability steels. The method employs simultaneous thermal analysis and thermomagnetic analysis; this combination of complementary analysis techniques is especially informative when transformations are accompanied by changes in magnetic state, as often occur in steels.

We applied this method in a survey of ASTM A723 steels that were prepared by various refining techniques (e.g., conventional, calcium injection, electroslag remelting (ESR), and vacuum-arc remelting (VAR)). Some surprising results were obtained, the most interesting of which is the large variation in hardenability among the steels. The implication is that the original TTT diagram of Heheman and Troiano must be applied with caution.

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[1]Heheman, R. F. and Troiano, A. R., Metal Prog., Vol. 21, No. 1, 1945, pp. 1-5.

We also sought to establish the relationship between the laboratory measurements of hardenability and properties of manufactured components prepared under various processes. For this purpose, we determined the mechanical properties of several large scale samples that were subjected to different heat treatments, and analyzed the mechanical property data for a large number of manufactured components of steels that exhibited different hardenabilities in our laboratory measurements. We find that the present hardenability data provide the basis for a consistent explanation of a broad range of mechanical property results on manufactured components.

EXPERIMENTAL PROCEDURES

The simultaneous differential thermal analysis (DTA) and thermomagnetic analysis measurements were conducted on a Mettler DTA/TGA analyzer. This apparatus was modified for the magnetic analysis by placing two sets of Helmholtz coils around the furnace in order to provide a magnetic force on the ferromagnetic sample. The standard Mettler furnace was replaced by an ASO Design Reg'd furnace which allows faster heating and cooling. Helium gas was used to provide optimum thermal response. The standard Kanthal furnace windings were replaced by Nichrome to eliminate artifacts introduced by the presence of ferromagnetic material.

The conventional sample geometry employed with this apparatus is cylindrical (¼-inch diameter, ½-inch height). With this sample shape, care must be exercised in interpreting the low-field (30 Oe) magnetic data because of nonlinearity introduced by demagnetizing factor effects (ref 2). Surface

[2]Bozorth, R. M., Ferromagnetism, Eighth Edition, D. Van Nostrand Co. Inc., Princeton, NJ, 1951.

decarburization during high temperature cycling can also generate spurious effects, especially with the magnetic technique; this problem is avoided by using a duplex copper-chrome electrodeposited coating over the sample.

Information related to hardenability is essential to this study and satisfactory measures of relative hardenability can be established with either DTA or magnetic analysis. Bainite hardenability, which is related to the sample's ability to avoid bainite on quenching, is of primary concern for quench rates employed in practice. We obtain a measure of this by selecting cooling rates that span a range of volume fractions of bainite formed.

In analyzing mechanical property data, we focus on the Charpy impact energies (-40°C), since this mechanical property appears to be the most sensitive to the presence of bainite in A723 (ref 3). In particular, the Charpy values of tempered lower bainite samples are about half that of the tempered martensite samples, while little difference is observed in other mechanical properties. Comparisons of Charpy values at a single temperature for A723 steel are considered appropriate here because Kendall (ref 4) has shown the fracture toughness to be insensitive to strain rate variations over five orders of magnitude and to temperature variations between -73°C to 23°C. Standard optical metallography does not provide a reliable measure of the presence of bainite, particularly for lower bainite, in mixed quantities, in a tempered sample (ref 5).

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[3]Nolan, C. J., Brassard, T. V., and Defries, R. F., "How Microstructure Influences Mechanical Properties of Forgings," Metals Engineering Quarterly, Vol. 13, No. 2, 1973, pp. 30-34.
[4]Kendall, D. P., "Effect of Loading Rate and Temperature on the Fracture Toughness of High-Strength Steels," Materials Research and Standards, Vol. 10, No. 12, December 1970.
[5]Samuels, L. E. and Rickard, C., Private Communication; Samuels, L. E., Optical Microscopy of Carbon Steels, American Society for Metals, Metals Park, Ohio, First Edition, 1980, pp. 33-34.

RESULTS AND DISCUSSION

Figure 1 shows typical DTA exotherms associated with the austenite transformations to bainite and martensite for ASTM A723 steels from different sources. These samples represent different refining methods, and analyses indicate small differences in the chemistries. The approximate M_s temperature is indicated by the arrow. Variations in M_s of the order of 10 to 20°C can be expected due to differences in chemistry and to the presence of bainite. The area under the curve above M_s is a measure of the amount of bainite formed, while the area below M_s gives the quantity of martensite formed. Furnace cooling was used to obtain these data; the corresponding cooling path is shown in the dashed line in Figure 2. The nonlinearity in the temperature axis of Figure 1 is due to the variation in cooling rate as shown in Figure 2.

According to the data shown in Figure 1, the largest amount of bainite forms in the calcium injected sample, a lesser amount forms in the conventionally prepared (electric furnace melted and vacuum degassed) steel, and no bainite formation is detected in the ESR refined sample. However, our survey of A723 steels from a number of suppliers who employ various refining techniques, indicates that hardenability correlates with sample chemistry rather than refining technique.

We distinguish low and high hardenability as follows. The calcium injected and conventionally refined samples of Figure 1 are typical of alloys that we classify as low hardenability. The low hardenability steels that we have analyzed have nickel concentrations near two percent. The ESR sample is typical of alloys that we classify as high hardenability. The high hardenability steels generally have nickel concentrations near three percent. Examples of composition analyses for samples from each of these categories are

given in Table I. It should be noted that for this high hardenability steel, one must employ a much slower (factor of 4 or 5) cooling rate than used in this test in order to observe any bainite formation.

TABLE I. CHEMICAL ANALYSIS OF SAMPLES FROM ESR, CONVENTIONALLY REFINED, AND CALCIUM TREATED STEELS

	C	Mn	Ni	Cr	Mo	V	P	S	Si	Cu
Ca-Treated	0.335	0.596	2.152	0.935	0.529	0.102	0.008	0.008	0.238	0.089
ESR	0.339	0.643	2.989	0.976	0.521	0.109	0.011	0.005	0.228	0.110
Conventional	0.331	0.548	2.124	0.936	0.482	0.123	0.010	0.009	0.174	0.106

Figure 2 shows cooling curve results obtained from the type of data shown in Figure 1. The position of the bainite knee labeled "standard" was deduced from the original TTT data of Heheman and Troiano using the method of Grange and Kiefer (ref 6) and the results are consistent with our data for low hardenability steels. The location of the knee for the high hardenability ESR refined steel was obtained using our method. The two krees shown in this figure represent the approximate range of positions observed in our survey of many A723 samples with nickel concentrations ranging between 2 and 3 percent.

Experiments were conducted on several seven-pound disks of this high hardenability, ESR refined steel. The large size permitted the machining of samples for mechanical property measurements. Curve (a) of Figure 3 shows the cooling path of one of the steel disks under air cooling after a 1.5 hour austenitizing treatment at 843°C (1550°F).

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[6]Grange, R. A. and Kiefer, J. M., "Transformation of Austenite on Continuous Cooling and Its Relation to Transformation at Constant Temperature," Trans. ASM, Vol. 29, No. 1, 1941, pp. 85-116.

Notice that the heat release during the martensite transformation is sufficient to produce a substantial temperature increase. This phenomenon, which is termed "recalescence" (ref 7), represents one of the major differences between laboratory measurements on small samples (~ 6 grams) and results on large scale components. (Recalescence is not observed in our small samples because the surface-to-volume ratio is large enough to preclude a temperature rise during air cooling.) This is important because it is known that interrupted cooling (i.e., a temperature rise or an isothermal hold) below M_s will produce lower bainite in 4340 and our magnetic measurements indicate that the same is true for ASTM A723. For larger samples, the temperature rise is expected to be higher, resulting in more bainite formation; it appears that this is the primary factor limiting the practical reduction in quench rate in large components.

After cooling (Figure 3(a)), this disk was tempered for 2.5 hours at ~ 590°C (~ 1100°F) and a pair of Charpy specimens and a pair of tensile specimens were prepared. Test results were 1115 MPa (161.7 Ksi) and 1120 MPa (162.5 Ksi) for yield strengths and 44.7 nt-m (33.0 ft-lbs) and 49.5 nt-m (36.5 ft-lbs) for Charpy values at -40°C. These values are comparable to the values obtained for a full scale component of this steel that was prepared under standard manufacturing procedures (see Table II) which employs a factor of three or four faster quench rate. Thus, the present results for this alloy suggest that a reduction in quench rate is permissible if necessary to reduce distortion or the threat of quench cracking.

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[7]Hollomon, J. H. and Jaffe, L. D., Ferrous Metallurgical Design, Second Edition, John Wiley and Sons, New York, 1948, p. 66.

We performed a second experiment on an essentially identical disk of the same steel using a cooling path (Figure 3(b)) which represents an even slower quench to M_s, but avoids recalescence effects. This was accomplished by wrapping the disk in an insulating blanket after removal from the austenitizing furnace to slow the cooling until the disk temperature had reached the M_s value, which is well below the bainite knee. At $T \approx M_s$, the disk was removed from the insulating blanket and water quenched. The success of this experiment in confirming the high hardenability of this alloy was exhibited in dramatic fashion as the sample developed very severe quench cracks, clearly indicating the absence of significant amounts of the softer bainite phases. This conclusion is supported by hardness measurements on various portions of the disk which yielded values in 55-56 R_c range, again indicating that it was fully martensitic. This result is an adequate illustration of the point that the bainite knee is shifted by an order of magnitude in time, in agreement with the laboratory results as shown in Figure 2.

In order to relate laboratory results to manufacturing variables for ASTM A723 steels, we examined the mechanical properties of manufactured components of different sizes and different hardenabilities. In particular, we compared the properties of thick (~ 3-inch to 4.5-inch wall thickness) and thin (~ 1.7-inch wall thickness) sections of a given component that had been quenched by water spraying. This difference in wall thickness results in different quench rates, so we expect mechanical properties of thick and thin sections to vary in a manner controlled by the hardenability.

Table II lists mechanical properties, component thicknesses, estimated quench times, and relative hardenabilities (rated according to Figure 1). The mechanical property values are averages of results on approximately 20 randomly selected components of each of the three steels represented in Figure 1.

Yield strength values are included to show that the differences in Charpy values are not attributable to differences in tempering treatments (i.e., the yield strength is relatively insensitive to the presence of lower bainite (ref 3), but is a strong function of tempering treatment). Standard deviations of the mean are given in parentheses; standard deviations are approximately four times larger for this sample size (20).

TABLE II. COMPARISON OF LABORATORY HARDENABILITY DATA WITH AVERAGED PROPERTIES OF MANUFACTURED COMPONENTS

	Refining Method		
	ESR	Conventional	Calcium
Hardenability Rating	High	Low	Low
Quench Time (Thick)	25 min.	12 min.	12 min.
Quench Time (Thin)	10 min.	4 min.	4 min.
Av. Charpy (Thick)	56 (±1) nt-m	24 (±1) nt-m	24 (±1) nt-m
Av. Charpy (Thin)	61 (±1) nt-m	30 (±1) nt-m	45 (±0.4) nt-m
Av. Y.S. (Thick)	1103 MPa	1131 MPa	1138 MPa
Av. Y.S. (Thin)	1103 MPa	1131 MPa	1138 MPa

Comparison of Charpy values and quench times shows a correlation with hardenability. For the high hardenability ESR case, for example, little bainite is expected even for the very low quench rates (except for recalescence effects), so the similar Charpy values for the thick and thin sections are as expected. For the low hardenability calcium treated steel, on the other hand, the tendency to form bainite is so large that a substantial amount

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[3] Nolan, C. J., Brassard, T. V., and Defries, R. F., "How Microstructure Influences Mechanical Properties of Forgings," Metals Engineering Quarterly, Vol. 13, No. 2, 1973, pp. 30-34.

is expected; therefore, the large property differences between thick and thin sections reflect the dominant role of bainite hardenability in this case. Similar data taken from low hardenability calcium injected steel components, quenched at a more rapid rate (8 minute quench time), show a large increase in Charpy values (to 26 ft-lbs, average) for the thick sections. This is a further demonstration of low bainite hardenability. The implication for manufacturing is that components of this steel should be quenched rapidly (quench time $\lesssim$ 8 minutes) to optimize properties. The data on the conventionally refined steels on the other hand, indicate that impurity effects play a larger role in limiting Charpy values than does bainite.

It should be stressed that low hardenability does not imply inferior steel; as indicated in Table II, the calcium treated steel which has the lowest hardenability according to Figure 1, exhibits better properties than conventionally refined steels if the proper quench rate is used. Another point illustrated by the results in Table II is that the mechanical property enhancement (Charpy value) is directly related to secondary refinement.

SUMMARY AND CONCLUSIONS

A combined thermal and magnetic analysis method was developed and applied to study austenite transformations in ASTM A723 steels. Data relating to bainite hardenability are reported for steels prepared by various refining techniques. The principal result is that very large variations in hardenability are found among steels from different sources, and this variation appears to be due mainly to variations in nickel composition of less than one percent. Mechanical property data on manufactured components of A723 steel that were processed under different conditions exhibit features that are consistent with these laboratory results on hardenability.

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7. Hollomon, J. H. and Jaffe, L. D., Ferrous Metallurgical Design, Second Edition, John Wiley and Sons, New York, 1948, p. 66.

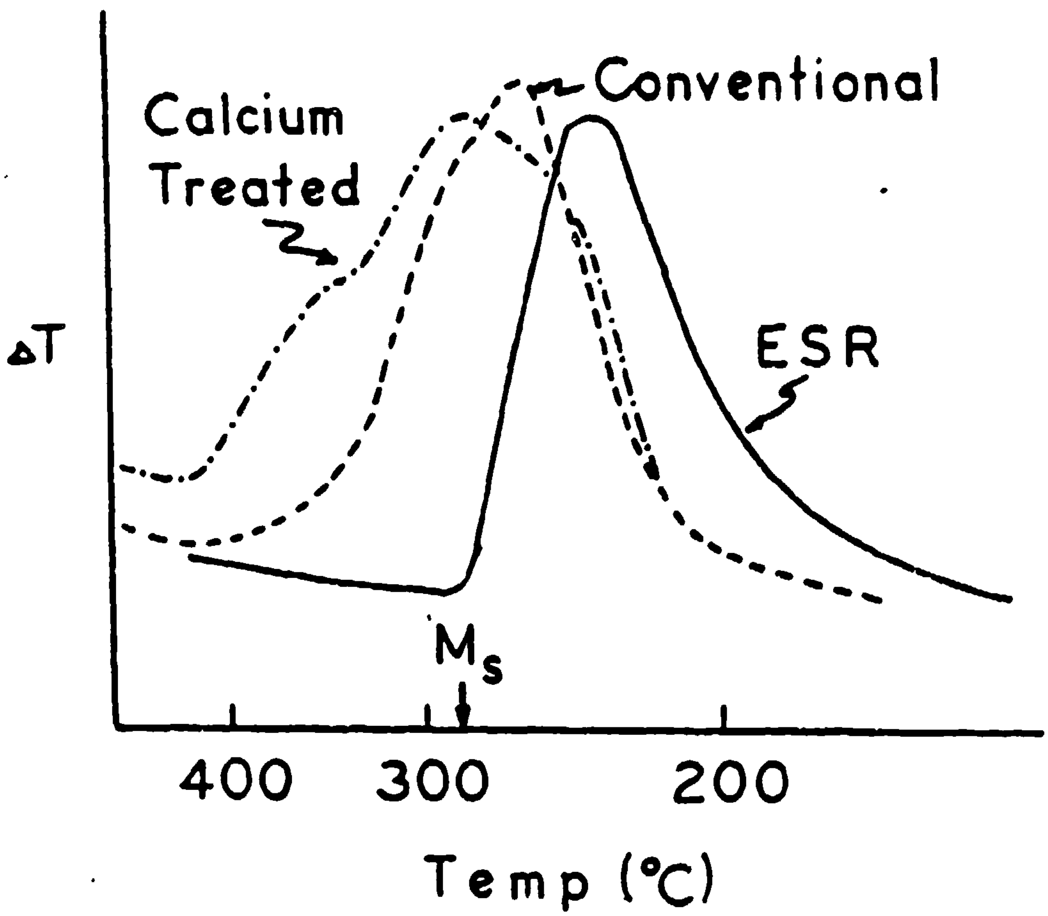

Figure 1. Differential thermal analysis output during continuous cooling of various ASTM A723 steels from the austenite temperature.

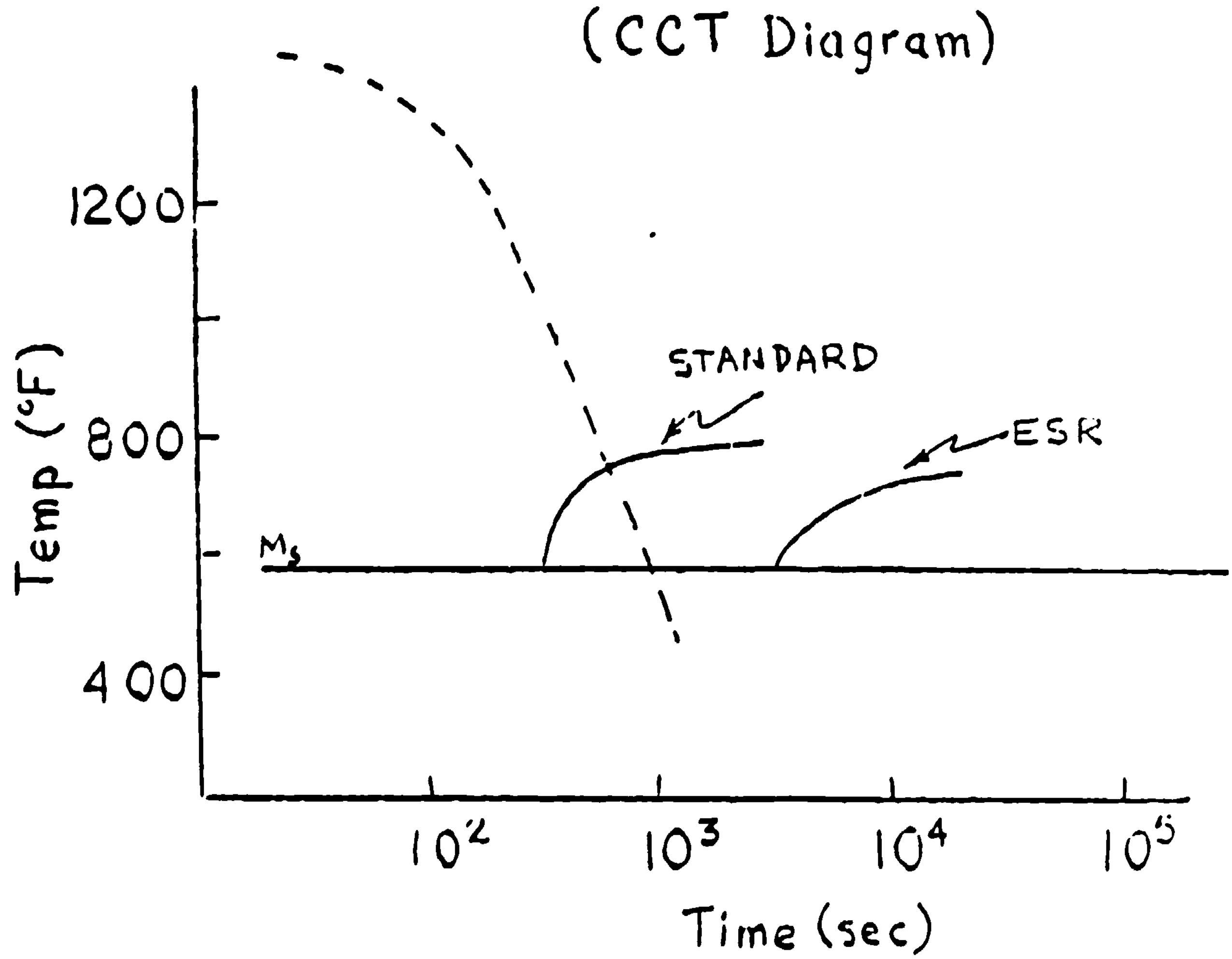

Figure 2. Continuous-cooling-transformation curves for ASTM A723 steels from different sources. The dashed line represents the cooling path used to obtain the data in Figure 1.

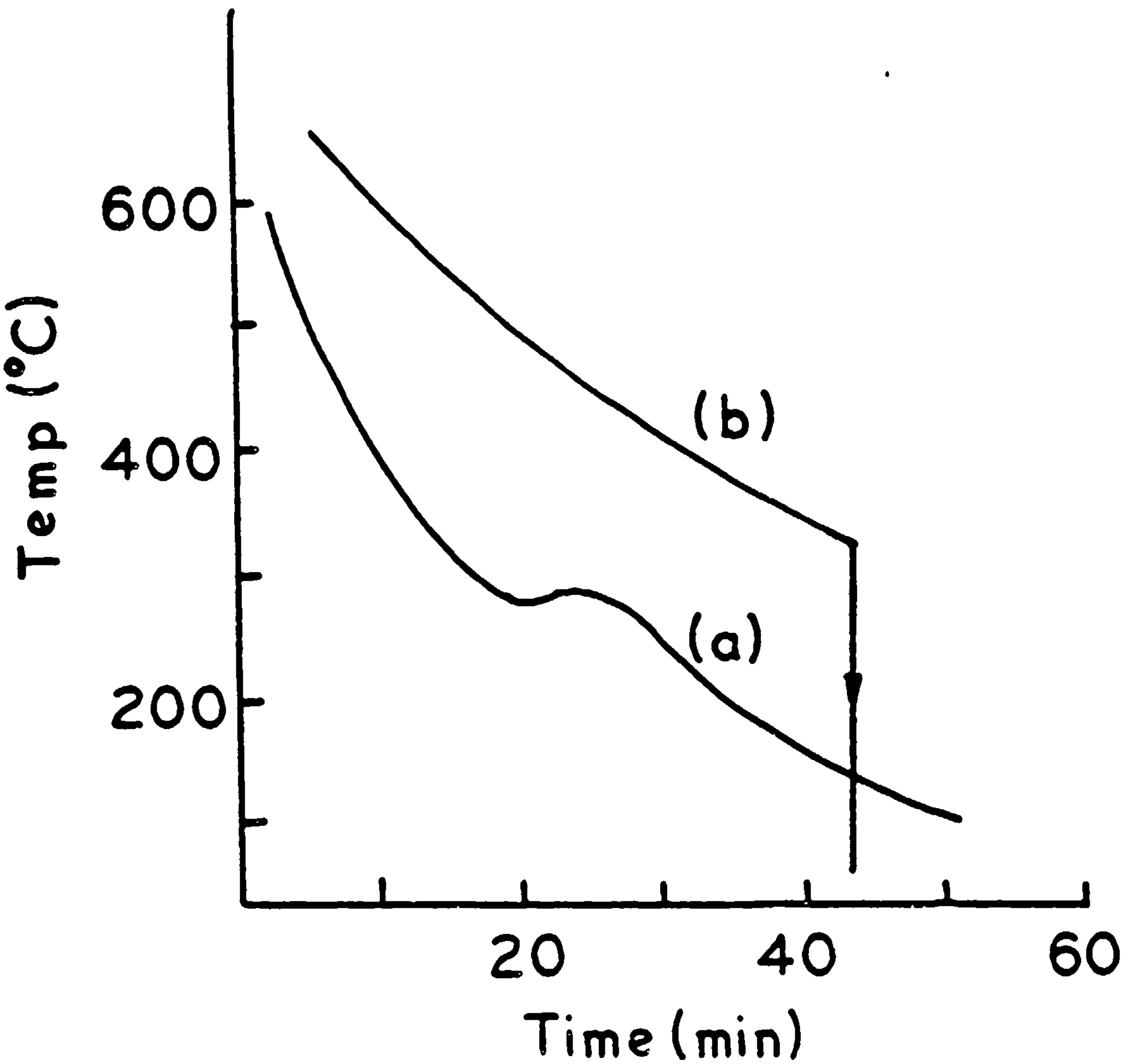

Figure 3. Slow-cooling experiments. Figure 3(a) shows the time-temperature path recorded for air cooling of a seven-pound disk after austenitizing. Figure 3(b) shows the path for an insulated disk which was water-quenched from just above the M_s temperature to avoid recalescence effects.

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